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THESIS

PLANNING FOR RECALL OF MAINTENANCE MANPOWER

by

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September 2015

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Mission availability is a key component of system effectiveness wherein manpower forms a critical part of the resource requirements. Within the United States Air Force, military technicians supplement essential maintenance and logistics support for fighter aircraft. Under certain conditions, the placement of these technicians in their roles as reserve personnel creates disproportionate economic loss for the parent unit and the reserve unit. The results of an analysis of the F-15D fighter aircraft indicate that the organization costs of the military units have a significant effect on how long a reservist should partition duty between the military units to achieve a minimum loss for both the parent unit and the reserve unit.

This research suggests another motivation for splitting the reservist's time between the parent and reserve units. The methodology of using loss functions to address manpower allocation can be similarly applied to other areas where there is concurrent demand for the same personnel.

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PLANNING FOR RECALL OF MAINTENANCE MANPOWER

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ABSTRACT

Mission availability is a key component of system effectiveness wherein manpower forms a critical part of the resource requirements. Within the United States Air Force, military technicians supplement essential maintenance and logistics support for fighter aircraft. Under certain conditions, the placement of these technicians in their roles as reserve personnel creates disproportionate economic loss for the parent unit and the reserve unit. The results of an analysis of the F-15D fighter aircraft indicate that the organization costs of the military units have a significant effect on how long a reservist should partition duty between the military units to achieve a minimum loss for both the parent unit and the reserve unit.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGR	Active Guard and Reserve
DOD	Department of Defense
EMMI	energy, matter, material wealth, and information
FTS	full time support
FWS	federal wage system
GS	general schedule
IMA	individual mobilization augmentees
ING	Inactive National Guard
IRR	Individual Ready Reserve
LTB	larger-the-better
MDT	mean maintenance downtime
MT	military technician
MTBF	mean time between failure
MTBM	mean time between maintenance
NTB	nominal-the-best
OSD/RA	Office of the Assistant Secretary of Defense for Reserve Affairs
RAM	reliability, availability and maintainability
STB	smaller-the-better

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EXECUTIVE SUMMARY

Under certain conditions, the placement of military technicians in their roles as reserve personnel creates disproportionate economic loss for the parent unit and the reserve unit. This research suggests another motivation for splitting the reservist's time between the parent and reserve units. The methodology of using loss functions to address manpower allocation can be similarly applied to other areas where there is concurrent demand for the same personnel.

For the U.S. Armed Forces, and in particular for this research, the military technicians (MTs) in the Air Force provide about 11% of the critical maintenance labor for fighter aircraft. These MTs are reserve personnel, civilians, and contracted employees (Office of the Assistant Secretary of Defense for Readiness & Force Management 2013, v). The MTs have "dual-status" appointments in their roles "as both federal civilian employees and military reservists" (Kapp and Torreon 2014, 6). MTs form the predominant component of the technician pool (approximately 96%), and account for approximately 41% of the entire U.S. reserve component manpower. Any activity that prevents an MT from performing his maintenance tasks to the betterment of their military department should be investigated to find inefficiencies and recommend solutions. This thesis explores the economic consequences of assigning MTs.

Usually, MTs fulfill their reservist duties where they work as civilian employees. Their place of civilian employment (i.e., parent unit) is also their place of work as reservists (i.e., reserve unit). However, situations arise that necessitate the assigning of the MT to a reserve unit that is different from his/her parent unit. In such situations, there will be competing demands for the same human resource by both the military and reserve units. This thesis investigates the loss experienced by these units when operational priority results in the assignment of an MT away to a reserve unit.

Loss functions are established for the respective stakeholders based on maintenance scheduling for the F-15D fighter. The results from the analysis show that if the reserve commitment of 14 days can be allocated between the parent unit and the

reserve unit (rather than 14 days at only one of the units), then there can be an accommodating for the losses incurred by both military units. These relative losses between the military units are directly related to the difference in organizational costs of the two military units.

The results of an analysis of the F-15D fighter aircraft indicate that the organization costs of the military units have a significant effect on how long a reservist should partition duty between the military units to achieve a minimum loss for both the parent unit and the reserve unit.

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I. INTRODUCTION

A. OVERVIEW

A weapon system's "effectiveness [is] defined as the probability that the system can successfully meet an overall operational demand within a given time when operated under specified conditions or the ability of a system to do the job for which it was intended" (Blanchard and Fabrycky 2011, 427). There are three key components which make up system effectiveness: a) capability, b) availability, and c) dependability (Blanchard and Fabrycky 2011, 428). System capability is related to how well the system can address its intended function. As noted by Barringer (1997, 4, 9), system availability is related to the period that the system is deployable for operations (up-time) as compared to the period that it is in an inoperable state (down-time). For system dependability, it is a measure of the "degree to which a system is operable at any random time during a specified mission profile, given that its services are available at the start of the mission." and is an aggregate of measures such as safety, security, survivability, reliability, and availability (Melhart and White 2000, 1).

In today's context, ensuring system availability will take on an increasingly important role in addressing military operational requirements. Studies have shown that the developmental cost growth for new weapon platforms is increasing (Younossi, Arena, Leonard, Roll, Jain, and Sollinger 2007, 45):

> Despite many efforts and numerous recommendations to improve the acquisition process, cost growth of DOD weapon systems remains high. Development cost growth for completed programs is about 60 percent, most of which occurs early in the development phase. Further, our analysis of completed programs shows that longer programs experience higher cost growth than the average DCGF for all programs. Moreover, electronics programs have the lowest cost growth, and that difference was statistically significant. Perhaps the most important finding of this analysis is that the trend of the average development cost growth for all weapon systems included in our data over the past three decades has remained high, without any significant improvement. (Younossi, Arena, Leonard, Roll, Jain, and Sollinger 2007, 45)

A key determinant of this increased cost growth is that most Department of Defense (DOD) development programs involve the incorporation of more complex technologies contributing to higher costs in maintenance. This introduces uncertainty in schedule planning (Younossi et al. 2007, 46). Coupled with budget limitations, this trend of increasing cost results in delays to new system acquisitions and costlier maintenance. Prime examples of cost growth are advanced fighter aircraft. Thus, in order to address current operational requirements for fighter aircraft, it is essential to ensure that the availability of existing weapon systems is maintained.

System availability is dependent on the system reliability, system maintainability and supporting logistics and administrative processes (Blanchard and Fabrycky 2011, 426). While system reliability affects how frequently the system is down due to failures, a function of design parameters, maintainability affects how fast the system can be recovered to a serviceable state, which is dependent on the time taken to carry out maintenance and the availability of administrative and logistics support, such as availability of spare parts, support equipment and trained personnel. To maintain a high-level of system availability, it is critical to ensure continual sustainment of logistics and administrative support for ready availability of resources over the system's life cycle.

The sustainment of military systems is carried out by the military technicians (MTs), who comprise approximately 96% of the technicians. Since MTs are federal civilian employees, Congress has purview over the rules for their end-strength number, benefits, retirement regulations, and general policy. The MT program has been around since the National Defense Act of 1916 (Kapp 2000), whereby MTs simultaneously serve in the military as reservists and as federal employees as civilians.

The objective of maintenance is to provide mission capable aircraft. An increase in MT support correlates with an increase in the number of mission capable F-15Ds (Oliver et al. 2001). To address maintenance and logistics operations, a range of resources are required which includes hardware such as system spare parts (spares), support and test equipment, information such as technical servicing manuals and documentation, as well as qualified manpower to carry out maintenance and other support activities such as training and inventory management. For maintenance resources

such as spares, support and test equipment, the scope of use is generally limited to specific platform types. For example, component spares dedicated for a particular aircraft model are not able to be used on another aircraft model; servicing instructions are drafted based on the specific requirements of a particular weapon platform and are not useable on other platforms. Maintenance specialization is often a critical factor considering that familiarity with the platform expedites its return to operations. In contrast, the element of manpower resources can take on a more versatile role. The specifics or the degree of specialization is a factor that should be considered in a determination of loss. For example, a vehicle mechanic can be qualified to maintain a variety of ground vehicles, ranging from armored tanks, infantry vehicles to trucks, where this possession of a suite of skill sets will enable him/her to be deployed effectively across different domains in the same occupation with same duties. In this case, the loss incurred can be minimized with cross training. Therefore, a critical need for maintenance may be offset by using a pool of cross-trained MTs. However, an implication arising from this cross-equipment versatility is the emergence of a competing demand for different jobs that must be reconciled with the allocation of that sole human resource. This allocation management issue is compounded when the resource pool is finite or limited to only a few individuals.

B. OBJECTIVE

In view of the potential competing demands for the same maintenance manpower, the objective of this thesis is to examine how these demands can be managed within a military context to reduce overall costs to both the reservist and parent units.

At least two situations may arise that necessitate the assigning of the MT to be a reservist for a different parent unit. These situations include 1) the need to address the MT's progression in rank, where the parent unit does not have sufficient positions for promotion of the MT, and 2) the need to augment the reservist pool of a different parent unit in preparation for a surge in operational requirements. In these situations, the support services of the MT will have to be co-shared with a separate reserve unit. The parent unit incurs a loss of its MT while he is on duty at the other reserve unit. And if the maintenance work is not completed in the 14-day period, the reserve unit experiences a loss of the equipment while it requires continuing repair. The level of loss incurred is

dependent on the duration of the reservist recall period, the amount of labor expended during the recall period, and the amount of time spent by the MT to effect maintenance and repairs.

For this research, the losses are predicated on the hourly expenditure of dollars for a specific platform (i.e., $17,000 per hour for the F-15D fighter aircraft) versus an administrative task that supports maintenance (i.e., $328 per hour for handling paperwork). The worker is paid the same amount per hour (for example, assuming no premium is paid for hazard duty or locale adjustment) regardless of the task assigned, as long as the diversity of work tasks fall within the worker's occupation duties. This perspective is the accepted basis for cost accounting worldwide.

The focus of this thesis is to investigate a problem that arises when there is competing demand for the services of the MT by maintenance personnel in the U.S. Air Force reserve units that are not the MT's parent unit. From the perspective of the parent unit, the problem is the loss of an employee for fourteen days and the resultant delay in work that the MT was doing. From the perspective of the reserve unit, the problem is the reduction in availability of much needed aircraft, if the MT does not spend fourteen days supplementing their maintenance efforts. Both the parent unit and the reserve unit need to establish a way of managing the flow of MTs between the roles of civilian employees and reservists under military and reserve units. Since the duration of reservist duty is two weeks for this research, if the time to satisfy the operational requirement was less than two weeks and the MT did not return to the parent unit, the parent unit would continue to experience a loss for any time away from the parent unit. However, if the operational need in the reserve unit is satisfied in less than two weeks, then the MT could return to his parent unit to serve the remaining time as a reservist. Even though such arrangements for splitting the reservist's time are possible under existing policy, the economic impact on the parent and reserve units is not discussed in the literature. This thesis investigates the implications for economic loss as part of the decision calculus for splitting time between the military units. Partitioning the reservist's time between a parent unit and a reserve unit is not common practice. However, this shared utilization of MT's labor may minimize the loss incurred by the parent unit, while satisfying the reserve unit's need.

Both units will experience loss given the circumstances that allow for the return of the MT to the parent unit before the end of the 14 days.

A priority need can arise that influences the number of days in which an MT is away from the parent unit. A priority reflects the urgent need for maintenance labor to increase the availability of aircraft. If that priority need is satisfied before the end of the 14-day period, the MT could return to the parent unit, thereby minimizing the loss to the parent unit. It can be the priority maintenance need that precipitates the change in duty for the MT for an upcoming reserve period. While other conditions apply for change in duty station, this example based on priority is used to demonstrate the utility of a loss function for thinking about the costs and tradeoffs that affect the costs of maintenance.

Retaining the MT beyond what is necessary to satisfy the operational needs of a reserve unit causes harm to carrying out the work tasks of the parent unit. The causing of *undue* losses to the parent unit depends on the total hourly costs attributable to the maintenance work in the parent unit. The loss incurred by the reserve unit depends on the total hourly costs attributable to the maintenance work in the reserve unit if the MT does not complete the maintenance that is planned for the 14 days. In the extreme, if the maintenance work on the equipment is never completed, then the reserve unit experiences a complete loss of the use of the equipment, i.e., its replacement cost.

The benefit of solving this problem is there may be instances when an optimum reservist recall period can be adjusted to minimize the total loss incurred by both units. Policy issues are important, however they are outside the scope of this research.

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II. CONTEXT

In order to sustain daily operations in military commands, units in the military reserve are made available for work. Their duties include "to organize; administer; instruct; recruit and train; maintain supplies, equipment and aircraft; and perform other functions" (Kapp and Torreon 2014, 5–6). The pool of full time support (FTS) personnel consists of the following five categories: "Active Guard & Reserve, Military Technician, Non-Dual Status Technician, Active Component, and Civilian" (Kapp and Torreon 2014, 6). Two consequences of reservists filling positions to support operational needs are the reduction in labor expenses for work performed and the growing dependence of the operations forces on the value added by the reservists. The short-term benefit of the reduced manpower costs in a budget-constrained environment is offset by the command's reliance on the two-week reserve duty to carry out maintenance. As the demand for supporting operational requirements shifts from full-time military personnel to the reservists, the harmful consequences increase for not having access to the people on whom the force is becoming more reliant. The relative proportions of the reserve manpower size are illustrated by Table 1.

Table 1. Proportion of Reserve Component Manpower (from Kapp and Torreon 2014, 8)

Table 2. Reserve Component Full Time Support Personnel as of September 30, 2013

	Active Guard and Reserve	Technician[a]	Active Component	Civilian	Total
Army National Guard	31,111	27,393	184	785	59,473
Army Reserve	16,372	9,040	68	3,060	28,540
Navy Reserve	10,143	0	1,948	782	12,8732,873
Marine Corps Reserve	2,244	0	3,778	293	6,315
Air National Guard	14,557	22,568	208	208	37,541
Air Force Reserve	2,813	8,992	521	3,865	16,191
Total	**77,24077,240**	**67,99367,993**	**6,707**	**8,993**	**160,933**

Source: Data provided by the Department of Defense

a. Includes Dual Status and Non-Dual-Status Technicians

Approximately, 12% of the technician reservists are MTs. In the special case of National Guard MTs, the Federal law governing MTs is known as the Technician Act, Title 32. Under Title 32, these MTs are not to be compensated for irregular or overtime work. It is observed that in recent years there is a gradual decline in the number of MTs. Since 1998, a budget low in the past 40 years (Lawrence 2000), the number of MTs has decreased. Not surprisingly, the sophistication and specializations of the MTs have increased dramatically in these past 15 years, requiring a greater number of technicians than indicated in Table 1. Consequently, higher annual compensation is paid – nominally $87,060 (in FY2000 dollars), including wages ($65,364), benefits ($19,606), education ($1,200), and training ($900) (USAF 2015, BLM 2015).

There are both incentives and disincentives to being an MT. Extrapolating the MT's average pay plus benefits to FY2014 dollars, the MT takes increases to $100,000, or approximately a $30 million budgetary impact in 2014. Contrast that budgetary impact of the MTs in 1998 as $163 million, in 2014 dollars (ODUSD(PI)(RQ) 1999). There is a corresponding reduction of 81% in maintenance technicians since 1998. The sophistication of the aircraft has increased significantly and is now creating severe issues with operational readiness. In 1982, MTs were half of the military maintenance workforce. Now at 96% of the technical workforce, the MTs are more important than in previous years. Their impact on operational readiness is a topic for Congressional Inquiry and DOD policy to develop incentives to attract and keep the MTs working.

III. PROBLEM DEFINITION: DEMAND FOR MILITARY TECHNICIANS

For the MTs, the existing regulation states the following: "Unless specifically exempted by law, each individual who is hired as an MT (dual status) after December 1, 1995, shall be required as a condition of that employment to maintain membership in—(A) the unit of the Selected Reserve by which the individual is employed as a military technician; or (B) a unit of the Selected Reserve that the individual is employed as a military technician to support" (House Committee on Armed Services 2011, 2229–2230). Currently, the policy for managing MTs allows for assigning them as a reservist to the same organizational unit that he or she works for as a civilian under certain conditions. Under this policy, there should be negligible disruption to the support that the MT provides when transiting between the civilian and reservist roles. However, based on regulation clause (B), there is a possibility that the MT will be assigned to another reserve unit that is different from his or her primary place of employment (referred to as the parent unit). Reasons that can lead to this scenario are as follows:

- Route of Advancement Opportunities—As military reserves, MTs are expected to qualify for military promotions (Cage 2000, 7). With a smaller number of positions left available at the higher echelons, it is expected that the MT will have to be tagged to a separate unit, if his or her original unit does not have sufficient positions available to address promotion requirements.

- Surge in Operational Requirements—With the increasingly significant role played by the reserve components in military operations, certain reserve units may experience a surge in operational requirements, which translates to an increased need for logistics and maintenance support. In cases where the reserve unit's organic manpower is not sufficient to address the increase in requirements, additional manpower, inclusive of

MTs, will need to be transferred from other units so as to augment the manpower supportability.

In the event that the MT has to support a reserve unit in his or her reservist capacity, this change from work in their parent unit may give rise to a competing demand for his or her service support. During the period that the MT reports for reserve duty in the reserve unit, there will be a “loss” in supportability for his or her civilian employment unit (the parent unit). When the MT completes his or her reserve obligation and returns to the parent unit, there will be a corresponding “loss” in supportability for his or her reserve unit. The losses that are incurred by both parent unit and reserve unit are an issue that forms the focus for the thesis. The research question can be stated as follows:

How can the loss incurred be reduced by both parent unit (the reservist’s civilian position) and reserve unit due to the transition of MTs between the roles of civilian employee and reservist?

An investigation into the stakeholders involved with the military and reserve units provides information on the differences between the needs of the parent unit and the reserve unit.

IV. STAKEHOLDERS AND SCENARIOS

Stakeholders are those individuals and organizations who either have an interest in the outcome of solving a problem or who are causing loss to another stakeholder who also has an interest in the outcome of the event. A stakeholder can be defined as "an entity (a person either acting alone or representing an organization) who can influence the conceptualization or funding of the development project, or the product's or service's acceptance, operations, or disposal" (Langford 2012, 259). "A stakeholder is anyone who significantly affects or is affected by decision-making activity that influences the product or service, where in a broader sense, it is someone with an interest or concern, and specifically someone at risk due to the product or service" (Langford 2012, 259). The three key stakeholders that should be considered are the parent unit, the reserve unit, and the MT. In this research, the perspectives and needs of the parent and the reserve units are used to develop a loss function which models the losses incurred by parent unit and the reserve unit based on the time spent by the MT with each unit. The impacts of the MT and the secondary stakeholders such as the MT's family members are important for retention of the MT, but are out of scope for this research.

A. MEASURE OF PERFORMANCE

The development of measures of performance is common in military and commercial applications. For example, decisions concerning allocation of scare resources (Langford 2012) applies to both realms of these applications. A means of evaluating the measures of performance is to consider an optimum target that is achievable within a range of less-than and greater-than performances that specify the limits of acceptability. Variances from the target performance can be either equal in their deviation or skewed in favor of the less-than specification or the greater-than specification limits (Appendix A).

To determine the relationship(s) between the losses incurred by the parent unit and the reserve unit, time (in 24-hour daily increments) was selected as the measure that captured the loss in terms of dollars. The effect of these losses on the MT and on the parent unit was reflected in the parent unit's total cost of carrying out their operations on

a daily basis. A daily rate of expenditures for each organizational unit was calculated (in the case of the parent unit), but based on published literature (for the reserve unit).

To determine the daily cost for the parent organization, the following scenario was developed to represent an extreme, but plausible contrast to the needs of the reserve unit. Like the reserve unit, the parent unit is responsible for maintenance on the F-15D. The timeframe for the scenario is within the ten years period between 1998 and 2008.

1. Parent Unit Situation

The parent unit is a small training unit that works on F-15D aircraft. While their parent duties are to be trained on maintenance procedures and repairs, they also carry out general equipment repair. They have one F-15D, normally 6 MTs, one certified pilot, and about half the parts stocked that they need at any one time. For the most part, their work is performed outdoors adjacent to a six room Quonset hut in the high desert of New Mexico. Recently, maintenance and repair work on the F-15D has stopped, while they await engine parts to complete their maintenance and repair tasks. Their organizational costs do not reflect the full depot costs associated with F-15D maintenance and repair, but rather are typical of administrative work, training, and light repair of air conditioners. On average, the 6 technicians from parent unit spend only 7% of their time on the F-15D, which is quite unusual. Whereas, the F-15D was mission capable 43% to 83% of the time (GAO 1982; 2003; NSIAD 1981), the parent unit's F-15D is mission capable only 0.01% of the time, or about a two-hour flight once per year.

The MT at the parent unit is paid the same amount per hour as the MT supporting the reserve unit (assuming no premium is paid for hazard duty or locale adjustment). All tasks assigned to the MTs fall within the MTs' occupation and duties of the jobs. Therefore, an MT's compensation is based on the occupation and duties of the job, but not on the value, mission, or value of equipment that is maintained or repaired by the MT. This perspective on cost accounting is commonly practiced worldwide in government, military and industry.

Since 97% of the work performed by the parent unit is administrative and light maintenance on the office air conditioner, an MT's cost per hour is nominally $328 (assuming a total of $87,060 in annual compensation (Table 2) plus overtime pay for 2 hours at 1.5x fully-burdened hourly rate). The hourly maintenance and repair rate for the F-15D in 2008 dollars was $17,000 (Senate 2009).

Table 2. Basic Labor Expenses for MTs Supporting F-15D

1st Fighter Wing, Langley Air Force Base, Virginia				
Wages*	$31.42/hr	$ 65,353.60	per year	Bureau of Labor Statistics
Training	$900.00	$900	per year	Estimated
Courses	$1,200.00	$1,200	per year	Estimated
Benefits*		$ 19,606.08	per year	Bureau of Labor Statistics
Total annual compensation*		$ 87,059.68	per year	or $41.80/hr fully burdened

Referencing data from the Bureau of Labor Statistics and Langley Air Force Base publication, http://object.cato.org/sites/cato.org/files/pubs/pdf/tbb-59.pdf

Organizational costs for the parent unit are based on 93% administrative work and light maintenance of air conditioning equipment and 7% maintenance and repair work on the F-15D. The parent unit's organizational cost for administrative and light maintenance is based on the hourly labor rate for the MT ($328, including 2 hours overtime per day). The maintenance, repair, and operational costs (electricity) of the office air conditioner adds an additional $0.52 per hour. The work on the air conditioning equipment assumes one $100 per repair (labor and parts) per year for 12 years + $2.60/hour for 350 hours of use + the purchase price of $600 + $350 for installation = $13,070 amortized over 12 years or $1,089 per year or $0.52 per work-day hour (2080 per year). All of the other expenses for the facilities, operations, supplies, transportation, communications, and support of the parent unit total $133,140 per year or $64 per hour, typical of a small training center located in New Mexico in 2003. The parent unit's organizational costs are $2,362 per hour.

2. Reserve Unit Situation

In contrast to the parent unit, the reserve unit is a large depot maintenance shop, with nearly 500 repair and maintenance personnel, 150 administrative personnel, and 40 pilots certified on the F-15D aircraft. The unit's organizational cost for maintaining and repairing F-15D aircraft is nominally $17,000 per hour (Senate 2009). Effectively, 100% of the organizational costs are focused on the maintenance and repair work on F-15Ds. The general maintenance characteristics of the reserve unit are as follows:

- 30 aircraft at the 1st Tactical Fighter Wing, Langley Air Force Base, Virginia (NSIAD 1991)
- $17,000 per hour of maintenance, in 2008 dollars (Senate 2009)
- MTs comprise 11.1% of the maintenance personnel at the 1st Tactical Fighter Wing F-15 (Langley 2008)
- Average flight time = 1.58 hours (in the ratio of 2,400 miles/1520 miles/ hour)
- Number of maintenance hours per hour of flight time = 34.74, based on 1.58 flight hours *22 hrs. of maintenance per flight (Airliners.net 2005)
- 8,000 equivalent flight hours (*Aviation Week* 2012)
- 375 flight hours per year over lifetime, with 8,000 equivalent flight hours in 21 yrs (GAO 2003)
- 237 flights per year at the average flight time of 1.58 hours
- 8,285 labor hours of maintenance per year to support one aircraft for 375 flights (22 hours of maintenance/flight hour * 375 flights per year)
- 43.45 hours/day of maintenance for 120 day or 5.43 maintenance people per day for 120 days
- Maintenance and repair work is usually performed in teams of 5–6 people (Langley 2009)
- Mission Capable Aircraft Availability ranges from 40% to 85% (NSIAD 1991)

- The rule of thumb for planning is that unscheduled maintenance is 50% of the scheduled maintenance workload (Alfares 1999)

3. Discussion of Parent Unit and Reserve Unit Situations

The differences between the total costs of maintenance for the parent and the reserve units are characterized as the costs attributable to the apportionment of work as are dependent on the levels of maintenance, the number of labor hours of maintenance; the various costs of labor, parts, facilities, supplies, and support; and the requirement for defect-free equipment during hours of availability, i.e., mission capable aircraft. Both units must delay maintenance due to shortages of parts. A depot may wait for parts or maintenance expertise or both for up to 57% of the time (GAO 1982). While waiting for parts for one aircraft, the reserve unit works on other aircraft. While waiting for parts for their aircraft, the parent unit spends 93% of their time working administrative tasks and performing light maintenance on their air conditioner. It is these differences that account for the significant differences in the organizational costs per hour for maintenance.

For this research, the losses are predicated on the hourly expenditure of dollars for a specific platform (i.e., $17,000 per hour for the F-15D fighter aircraft) versus an administrative task that supports maintenance training, i.e., $2,362 per hour for performing light maintenance on the F-15D, maintaining office air conditioners, and handling paperwork.

Note: The scenarios used in this research were constructed from a variety of published sources that viewed the F-15D as an aircraft with common problems and tractable solutions over a forty-year time span. The various sources present a consistent description of maintainability over the F-15 variants that were in service.

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V. DEVELOPMENT OF A MAINTENANCE MODEL FOR F-15D

The organizational costs for the parent unit and the reserve unit are attributable to the daily expenditures for labor, parts, outside services, and equipment to carry out their mission.

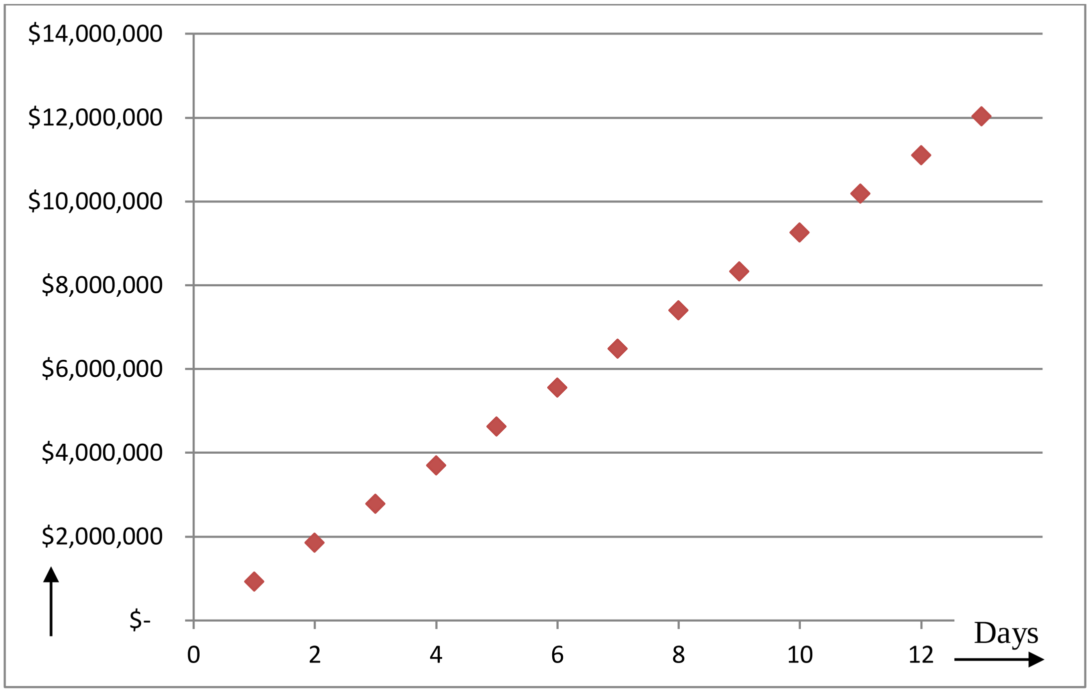
A. MAINTENANCE PLANNING FOR THE PARENT UNIT

Each day the average rate of costs are incurred at the rate of $392 ($328 per day labor plus $64 for all other expenses). When the MT is not working at the parent unit, the parent unit has lost the ability to have its work completed (without having a means to hire a temporary replacement). The loss can be thought of as a loss of control over the ability to have work done (i.e., started, continued, finished) according to schedule. The impacts of not keeping to schedule represent a loss to the parent unit. Two types of losses occur. First, there is a loss due to the variability in keeping to the schedule. When the MT stops working, the scheduled work is delayed, i.e., signifying variability in keeping to the schedule. The consequences of a delay represent a loss to the parent unit. Second, there is a loss due to the harmful consequences of missing the schedule of work. These losses could include not competing essential paperwork, not completing a maintenance check or a repair, or not returning the aircraft to mission capable readiness. The quality of the MT's work is considered good (acceptable) if the aircraft performs its intended functions, e.g., 'to take off', 'to fly', 'to carry out mission', and 'to land.' And, when the MT's work is not performed, then there is no work and therefore unacceptable performance.

With regards to replacement workers, they can be hired to replace the MT on a temporary basis if there is a contract or other means setup. Temporary replacement workers are typically billed at a premium to the costs of employees, and may; i) require additional instruction to carry out the work; ii)not present the appropriate skill set; iii) not be as productive as an employee; and iv) not be available when needed. Temporary workers may result in unacceptable losses. The decision to hire temporary replacement workers should be considered a schedule risk.

Given the losses due to variability in being able to stay on schedule with the work, and the risk of hiring acceptable replacement workers, an effective means of calculating the loss is to assume the loss is the daily organizational costs multiplied by the 14 day reserve duty ($5,488). Figure 1 illustrates these daily losses, a linear relationship, *x*.

Figure 1. Daily Losses to the Parent Unit when the MT Works at the Reserve Unit



B. MAINTENANCE PLANNING FOR THE RESERVE UNIT

The loss attributable to the reserve unit is also determined by their organizational costs to repair and maintain the F-15D. Each day of maintenance and repair work brings the aircraft closer to being mission capable. When an aircraft is taken out of service for repair and maintenance, the loss to operational availability is realized. That loss is reflected in the consequences of not having that aircraft when needed, and is valued up to the replacement cost of $30,000,000 ($24,400,000 basic fighter platform + $5,600,000 in "obsolescence upgrades" for the F-15D) (DOD 2014). If maintenance is not performed to return the aircraft to mission capable readiness, the loss is said to be infinite. In other

words, the loss is undeterminable. When maintenance technicians begin work on the out-of-service aircraft, the loss is reduced as the work progresses. This accounting approach of losses is consistent with Taguchi's work that relates the loss function to quality (Peace 1993).

The planning of maintenance and repair work for aircraft progresses according to a four-tiered level approach to inspecting, analyzing, evaluating, repairing, and testing commercial and military aircraft. The aim of this approach is to identify and confirm problems, anticipate and detail work, schedule work, secure needed resources, plan labor to satisfy schedule, do work, and evaluate work to determine mission capability. These functional requirements for aircraft maintenance have evolved over the past 50 years (Army 1960) to modern commercial and military aircraft (Sriram 2001). The Federal Aviation Agency requires frequent inspections of commercial aircraft as does the DOD with military aircraft.

1. Level A Maintenance

In addition to the walk-around check that is carried out by ground crews and pilots, a formal inspection (termed Type A or Level A) of engines, landing gears, control surfaces, tires, and gross structural defects occurs frequently. For military aircraft, Level A inspections can occur after every 10 hours of flight or approximately 60 times per year. Level B inspections occur after Level A inspections and often incorporate some or all of the tasks of Level A. The annual organizational costs of Level A inspections are $923,312 ($17,000 in reserve unit costs/ hour/year * 43.45 hours/day of maintenance for 120 day/year * 10 hours worked per day / 8 hours scheduled per day).

2. Level B Maintenance

Level B inspections and maintenance activities include a comprehensive visual inspection of the aircraft and lubrication of all moving parts (Sriram 2001). Due to the need to remove access panels on the aircraft's exterior so that systems and operational tests can be carried out, Level B work is sometimes performed inside a hanger. Frequencies for Level B inspections of the F-15D were extrapolated from flight times and the frequency of Level B inspections for commercial aircraft (American Airlines 2011)

based on the number of flights multiplied by the ratio of the speed of the F-15D to that of the Boeing 747 (Bandte 2000). Extrapolations of number of all maintenance events for military aircraft from the practices with commercial passenger aircraft (Transport Studies Group 2008; Squadron 2008; American Airlines 2011) are consistent with the maintenance experience of the 355th Maintenance Operations Squadron (Squadron 2008) and F-15 aircraft experience in the U.S. Air Force (USAF F-15 2007; USAF Factsheet 2006), that are categorized as Level A, Level B, Level C, and Level D inspections and maintenance events.

The annualized organizational costs of Level B inspections, maintenance, and repair are $2,215,950 ($17,000 in reserve unit costs/ hour/year * 43.45 hours/day of maintenance for 120 day/year * 24 hours worked per day / 8 hours scheduled per day). Level B work is modeled to occur after every 24 hours of flight or approximately 316 times per year. Level B work incorporates the inspections carried out in Level A and Level B may alternate with Level A inspections (Transport Studies Group 2008).

3. Level C Maintenance

Level C inspections and maintenance work include thorough service of the airframe structure, in addition to Level A and Level B work. Schedule, but non-routine maintenance is part of Level C work (Transport Studies Group 2008). Level C work on the F-15D is modeled as occurring twice per year for 40 hours per each of these maintenance events. The annualized organizational costs of Level C inspections, maintenance, and repair are $3,693,250 ($17,000 in reserve unit costs/ hour/year * 43.45 hours/day of maintenance for 120 day/year * 40 hours worked per day / 8 hours scheduled per day).

4. Level D Maintenance

Level D maintenance is the most comprehensive of all levels of maintenance. Level D occurs at depots that are equipped and staffed to completely disassemble, replace, and test all parts of the aircraft (Rand 2008). One Level D maintenance event occurs every 16.36 months with an annualized organizational cost of inspections, maintenance, and repair of $14,773,000 ($17,000 in reserve unit costs/ hour/year * 43.45

hours/day of maintenance for 120 day/year * 160 hours worked per day / 8 hours scheduled per day).

5. Model for Scheduling Maintenance Levels and Incurring Costs

There are two key reasons for scheduling maintenance based on the four-tiered level approach. Maintenance categorized and carried out based on Levels A, B, C, and D has been demonstrated to identify problems quickly to avoid hazards and to minimize expensive repairs, for example, that might result from small issues cascading into major problems; and secondly, to create a schedule for planning labor and resources so the maintenance can be performed in the most expeditious manner to return the aircraft to mission capability. The sequencing of levels of maintenance forms the schedule for planning labor needs, allocation of resources, inventory management for replacement parts, and repair operations.

Consider the following results from a sequence of maintenance events. During a Level A inspection, the maintenance team determines that the F-15D aircraft is flight-worthy for another flight. No unusual issues are noticed or carried over from a previous maintenance event. This evaluation means that the maintenance team did not find a problem that would jeopardize the safety of the crew or the aircraft, or compromise the availability for the next mission. In that case, a Level A inspection is scheduled to be carried out after next flight, which was planned for the following day. If there are no problems found after another Level A inspection after that next flight, then a Level B inspection will be scheduled after two flights. However, if a problem arises after tomorrow's flight, then the plan for a follow-on Level A inspection may be changed to a Level B or Level C maintenance event, depending on the nature of fault discovered during the first Level A inspection If a Level B maintenance was necessary and scheduled at the culmination of a Level A inspection, then the scheduler would know that one Level A had occurred, that a Level B was scheduled, and the day following the completion of that Level B there would be a Level A inspection planned. After completing any Level of inspection, the following day would normally be a Level A, as all problems are presumed to have been resolved. However, if a Level B inspection finds problems that require a Level C maintenance, then upon successful completion of the

Level C maintenance, a Level A inspection would be scheduled. In the manner of determining what should be scheduled, the commitment of maintenance funds is scheduled. It is that forecasting of maintenance labor needs that schedules the amount of funds that are planned to be spent during any 14-day period. Based on the historical costs for the F-15D fighter, models of maintenance schedules that project labor needs are established. The cost models for aircraft maintenance (Periyar Selvam et al. 2013) are important for budget utilization and end-of-year planning to increase the use of MTs, cannibalize parts from other aircraft, or defer various types of labor-intensive or skill-intensive maintenance. Table 3 models a sequence of maintenance event and assigns organizational costs for the Level maintenance of the reserve unit.

Table 3. Model Schedule for F-15D Maintenance at the Reserve Unit

Day	Level of Maintenance	Level $ for Maintenance	Cumulative $ Maintenance	Planned $	Days	$ Remaining from Day 14
1	A	$ 923,313	$ 923,313	$4,062,575	1-3	$16,804,288
2	B	$2,215,950	$ 3,139,263			
3	A	$ 923,313	$ 4,062,575			
4	A	$ 923,313	$ 4,985,888	$5,539,875	4-6	$11,567,801
5	C	$3,693,250	$ 8,679,138			
6	A	$ 923,313	$ 9,602,450			
7	A	$ 923,313	$10,525,763	$6,278,525	7-10	$4,985,888
8	B	$2,215,950	$12,741,713			
9	B	$2,215,950	$14,957,663			
10	A	$ 923,313	$15,880,975			
11	A	$ 923,313	$16,804,288	$4,062,575	11-13	$ 923,313
12	B	$2,215,950	$19,020,238			
13	A	$ 923,313	$19,943,550			
14	A	$ 923,313	$20,866,863	$ 923,313	14	$0
15	B	$2,215,950				

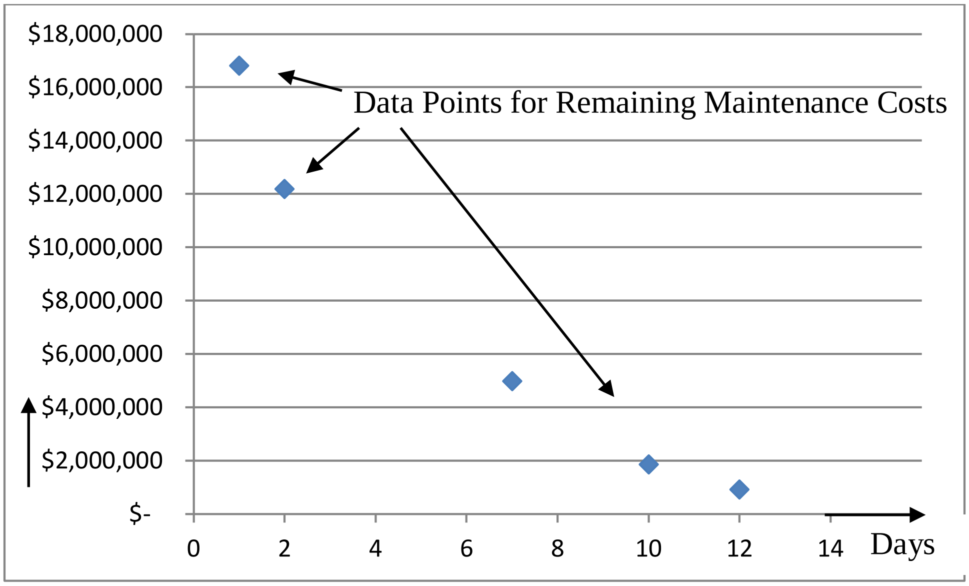
Knowing that a Level A maintenance on Day 1 required scheduling a Level B maintenance event on Day 2 indicates that on Day 1 a Level A and a Level B event was planned. Assuming the Level B was successful, then a Level A was planned on Day 3. Therefore, Table 3 would indicate Day 1_Level_A; Day 2_Level_B; Day 3_Level_A (with cumulative maintenance dollars of $923,313 + $2,215,950 + $923,313 =

$4,062,575). After the first three days, the amount of the remaining maintenance work scheduled to be accomplished during a 14 day period is $20,866,863 - $4,062,575 = $16,804,288. Scheduling of labor and allocating funds to the various maintenance accounts follows periodically throughout the 14-day planning cycle so that work crews can be scheduled efficiently. There are of, course, minor changes to the 3–5 day schedule, yet the planned commitment of funds tracks closely with historical data referenced in this Chapter.

One Level A maintenance event is scheduled for day 14, $923,313 remains to be spent. In this manner of calculating the “remaining” schedule of maintenance events with the commensurate reduction in the amount of planned expenditures, the loss of operational costs is determined. Concatenating a 3–5 day overlap with the previous scheduled maintenance events and then with the planned subsequent maintenance events is done to bridge the planning for the next 14-day period. A Level B maintenance event is shown for day 15, but not included in the budget allocation or planning for labor when the 14-day schedule was first developed. As the inspections reveal the actual need, day 15 may or may not be included in the 14-day period, but rather slipped into the next 14-day scheduling and planning cycle.

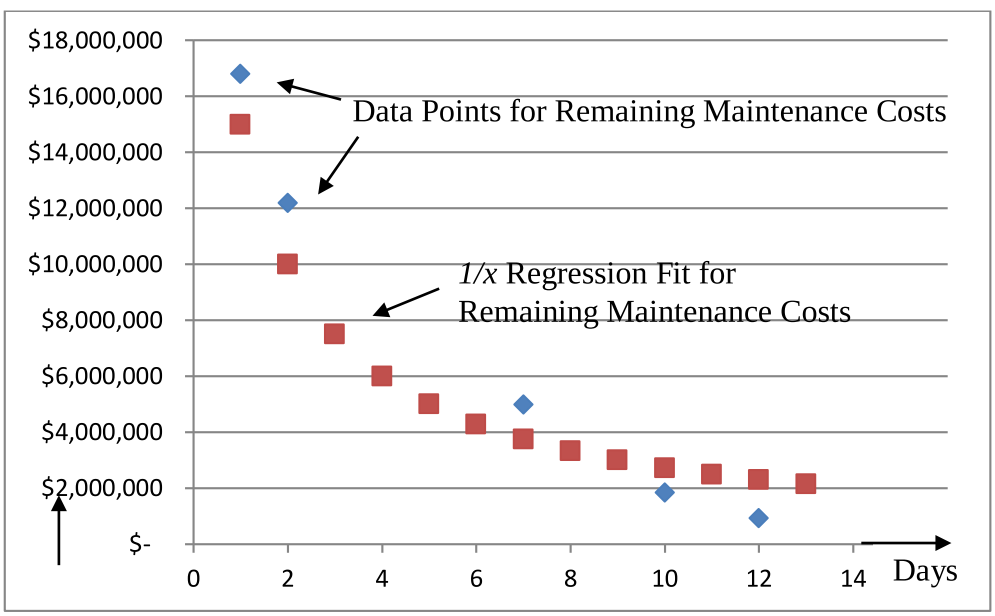
The scheduled maintenance events from Table 3 are shown in Figure 2.

Figure 2. Scheduled Maintenance Events for the Reserve Unit



A regression analysis of the data in Table 3 indicates a *1/x* dependency. Figure 3 correlates the maintenance data from the F-15D model with the *1/x* relation.

Figure 3. Scheduled Maintenance Events for the Reserve Unit Correlated with *1/x*



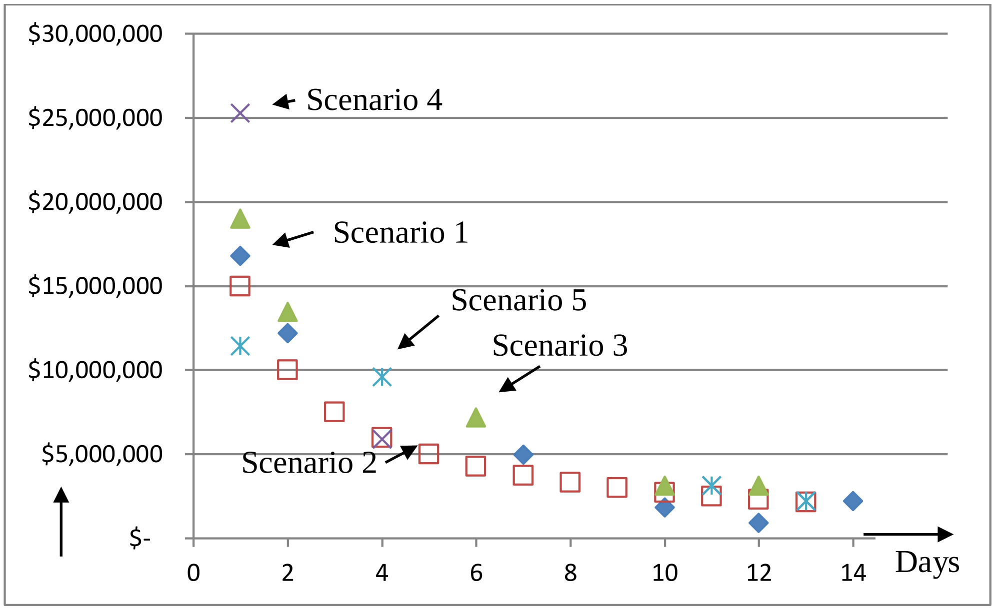
The scheduled maintenance events from the reserve unit model of 14-day scheduling and planning are plotted along with a *1/x* function (Series 2) where the day 1 data for *1/x* is scaled to equal 50% of the replacement cost of the F-15D. The differences in data points between the maintenance model and the *1/x* plot in Figure 3 on a particular day are whether a Level A or Level B event was scheduled.

By varying the mix of Level A's, B's, C's, and D's, according to their scheduled frequency, the data for the reserve unit's loss scatters about the *1/x* function (Table 4). The data from Table 4 is plotted in Figure 4.

Table 4. Four Different Maintenance Schedules Correlated with *1/x*

	Scenario 1	*1/x*	Scenario 2	Scenario 3	Scenario 4
Day	Scheduled Maintenance	$ 30,000,000	Scheduled Maintenance	Scheduled Maintenance	Scheduled Maintenance
1	$ 16,804,288	$ 15,000,000	$19,020,238	$ 25,298,764	$11,449,077
2	$ 12,187,725	$ 9,999,900	$13,480,363		
3		$ 7,500,000			
4		$ 6,000,000		$ 5,909,201	$ 9,602,452
5		$ 4,999,980			
6		$ 4,287,000	$ 7,201,838		
7	$ 4,985,888	$ 3,750,000			
8		$ 3,333,000			
9		$ 3,000,000			
10	$ 1,846,625	$ 2,727,000	$ 3,139,263		
11		$ 2,499,000		$ 3,139,263	$ 3,139,263
12	$ 923,313	$ 2,307,000	$ 3,139,263		
13		$ 2,142,000		$ 2,215,950	$ 2,215,950
14	$ 2,215,950				

Figure 4. Four Scheduled Maintenance Scenarios for the Reserve Unit Correlated with *1/x*



The scheduled maintenance events from the reserve unit model of 14-day scheduling and planning are plotted along with a *1/x* function where the day 1 data for *1/x* is scaled to equal 50% of the replacement cost of the F-15D. The differences in data points between the maintenance model and the *1/x* plot in Figure 4 on a particular day are whether a Level A or Level B or Level C event was scheduled.

VI. QUADRATIC LOSS FUNCTION FOR MAINTENANCE

A loss function maps the economics of events to capture key performances of stakeholders (Langford 2012, 298). More specifically, loss functions reflect the manner in which the economics are mapped according to normative principles (Murphy 1994) rather than how stakeholders view the situation.

Such is the make-up of a generalized loss function, where the loss in dollars is plotted as the dependent variable and the measure of performance is plotted as the independent variable (Appendix A).

A simple, yet widely applicable form of a loss function is the quadratic relationship $x+1/x$. When the parent unit has losses when the MT reports to the reserve unit and the reserve unit experiences a loss if the MT does not augment their aircraft maintenance labor force, the interaction between the two units through the actions of the MT results in losses that can be evaluated over the 14-day period for reserve duty. The assumption is made that the MT is fully capable to seamlessly fit into either the parent unit's work requirements or the reserve unit's requirements. Since the assumption is based on the reservists being immediately deployable, the model of losses does not include inefficiencies.

As shown, the loss for the parent unit increases monotonically in x. Whereas, the loss for the parent unit decreases as $1/x$. Whereas the literature on quality of services shows extensive use of quadratic forms of loss functions (Taguchi 1996; Chadha and Schellekens 1999) this thesis models the F-15D maintenance activities in terms of $x+1/x$, an asymmetric form of Taguchi's traditional form of $L = k\,(y\text{-}m)^2$, where L= loss in dollars; y = output mapping to the event; m = the target value of the output; and k = proportionality constant that when multiplied by $-m$, equals the minimum loss due to the interaction between competing stakeholder who want larger or smaller performance, x. The appendix illustrates the traditional Taguchi loss function and then derives a general loss function that in its simplest implementation reduces to $x+1/x$. While the traditional Taguchi loss function was developed for manufacturing of products, where control of deviation from a target value with small tolerances is shown to improve quality and lower

costs, the general loss function (Appendix) was developed to accommodate both statistical distributions as well as discrete, point solutions. For a more comprehensive analysis of maintenance scheduling, see Langford (2016).

A. USE OF LOSS FUNCTIONS FOR MANPOWER RECALL

A loss function is posed here as a mathematical structure for capturing the effect of negotiation or conflict between the parent unit and the reserve unit. The position that the reserve unit has a demanding operational need that has priority over a parent unit is determinable by the difference in the unit's operational costs, the consequence of not achieving or maintaining a reserve's mission capability for its aircraft, or other rational argument. The scenarios modeled for this research does not present a compelling argument why the reserve unit would have priority based on a relatively high operational cost/hour, only that it would benefit from the work of the MT and the loss to the parent unit does not emphasize mission capability, per se. The loss function will enlighten the discussion on the minimum number of days that the MT should be at the reserve unit so that both the reserve unit and the parent unit experience no more than the minimum loss. Here the minimum loss is determined as that experienced by both parties so that neither party has an advantage over the other party.

While several forms of the loss function can be employed for this analysis, the regression analysis shown in the previous section substantiates that a simple form ($1/x + x$), where the variable x is the time in days that the MT is away from the parent unit, compares reasonably with scheduling of actual F-15D Levels of maintenance.

The application of the loss function is shown through the impact of the MT's work on the operations of the parent and reserve units. For the parent unit, a longer reserve recall period will result in a longer period of absence of its MT employee, which translates to an increase in the "loss" that it has to bear. Thus, the applicable loss function is a smaller-the-better (STB) type, i.e., less time spent by the MT at the reserve unit, the better. On the other hand, for the reserve unit, the longer the MT works at the reserve unit, the higher the level of mission capability. Therefore, the applicable loss function for

the reserve unit is a larger-the-better (LTB) type. The Appendix discusses STB and LTB types of loss functions.

As the MT reserve time is relevant to the U.S. Air Force, analysis on the use of the loss function is carried out for both parent and reserve units.

B. COMBINED LOSSES FOR PARENT AND RESERVE UNITS

In simple form, the combination of a stakeholder with a requirement for STB and a stakeholder with a requirement for LTB loss is indicated as nominal-the-best (NTB). Adding STB and LTB over the time frame of the 14-day reserve duty, results in a minimum loss that occurs at 5 day (Figure 5). The data is indicated in Table 5.

Figure 5. Combined Losses for Parent and Reserve Units

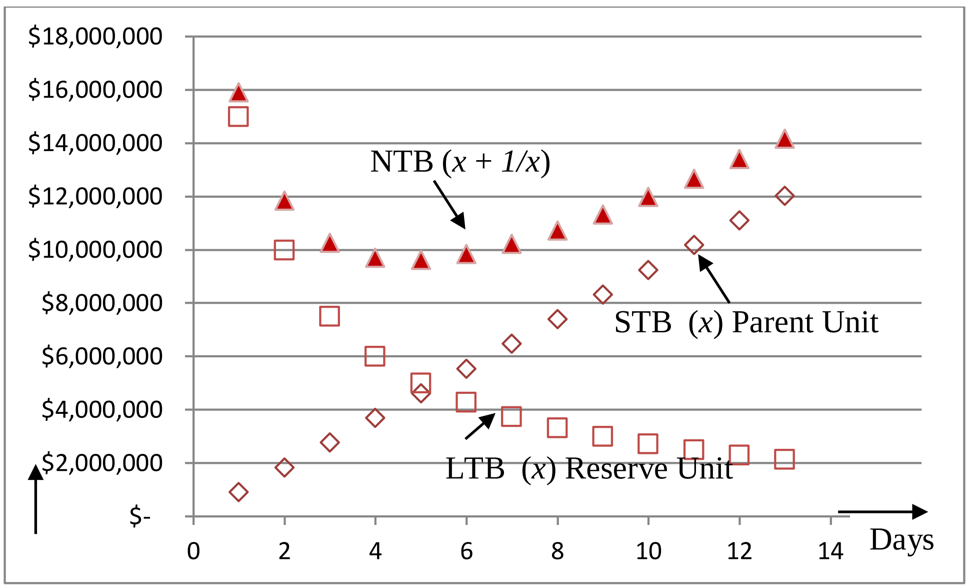


Table 5. Comparison of the Loss Function for the Parent Unit and the Reserve Unit

Day	STB (*x*)	LTB (*1/x*)	NTB (*x+1/x*)
1	$ 925,846	$ 15,000,000	$ 15,925,846
2	$ 1,851,691	$ 9,999,900	$ 11,851,591
3	$ 2,777,537	$ 7,500,000	$ 10,277,537
4	$ 3,703,382	$ 6,000,000	$ 9,703,382
5	$ 4,629,228	$ 4,999,980	$ 9,629,208
6	$ 5,555,073	$ 4,287,000	$ 9,842,073
7	$ 6,480,919	$ 3,750,000	$ 10,230,919
8	$ 7,406,765	$ 3,333,000	$ 10,739,765
9	$ 8,332,610	$ 3,000,000	$ 11,332,610
10	$ 9,258,456	$ 2,727,000	$ 11,985,456
11	$ 10,184,301	$ 2,499,000	$ 12,683,301
12	$ 11,110,147	$ 2,307,000	$ 13,417,147
13	$ 12,035,993	$ 2,142,000	$ 14,177,993

C. ANALYSIS OF RESULTS

Based on the correlation of loss functions to planning for the maintenance schedule, the significance of organizational costs is highlighted. Specifically, operational costs appear to be a key driver in determining the amount of loss experienced by the parent unit and the reserve unit.

Allocation of Reservists Time – The amount of time spent by the reservist at the parent unit versus the reserve unit is determined by the difference in the organizational costs of these military units. The larger the difference, the less the loss for one of the military units. If the organizational costs of the parent unit are equal to that of the reserve unit, then the time spent at both units should be approximately equal. In the example model of the F-15D there was a 7 times difference in organizational costs favoring the reserve unit. The loss due to the MT being away from the parent unit was a minimum at 9 days while the minimum loss for the reserve unit was at 5 days. In other words, both of the military units will experience a loss due to the reservist spending time at one or the other or both of the military units. However, there is period whereby the reservist can

work at both military units and provide a benefit to the maintenance efforts of both military units.

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VII. CONCLUSION

Mission availability is increased by maintenance. Scheduling of maintenance depends, in part, on the use of Levels to identify where and when maintenance budgets should be allocated. This thesis shows that budgeting of maintenance using the current system of Levels can be modeled as a simple loss function ($x + 1/x$). This loss function was used to investigate the budgetary consequences of five representative schedules of maintenance Levels to determine the impacts on military units whose labor is shared. These schedules follow a $1/x$ regression fit, when normalized to 50% of the replacement cost of the F-15D fighter aircraft. The correlation between actual F-15D maintenance budgets and a $1/x$ dependency on operational costs of the reserve unit suggests a new way of considering how priorities are set for assigning Military Technicians (MTs) to reserve units.

Scheduling Military Technicians (MTs) away from their parent unit for their reserve duty can create losses for both their parent unit as well as their reserve unit. The traditional views of scheduling an MT for reserve duty is for promotion and continuity of work that facilitates the mission of the parent unit without the MT performing the same duties as they perform in their civilian role. This research suggests that a priority is established by the difference in organizational costs of the military units that is in effect a priority weighting that may reflect the need of each military unit. The higher the organizational costs of a military unit, the greater the loss (without considering other factors, such as critical need). Critical need may be more important than organizational costs, depending on what is considered critical and the nature of the need. Other factors besides promotion, continuity of mission, and critical need, could include retention incentives and specialty training to facilitate a change in future work.

The F-15D maintenance data is well-ordered and piece-wise contiguous, in a mathematical sense. It are those properties, that facilitated the use of a loss function in a quadratic form, as observed and developed by Taguchi, for example.

The conclusion for this research is that the well-ordered maintenance data from the F-15D was correlated with a simple loss function. The general loss function in the Appendix also correlated (Langford 2016), but was not shown in this thesis other than to state that the form ($x + 1/x$) is the inherent underlying structure of the general loss function, and therefore will in general show the same correlative relationships.

Further, the higher organizational costs of a military unit were postulated to be a key variable in the quantitative investigation of how to assign MTs for their reserve duty. The strong correlation with actual costs was a surprising. The spread of the scheduling Levels was determined to be only one Level A, B, or C, representing a deviation from a true ($x + 1/x$) loss function of only 5–8%. While a correlation of scheduling of maintenance labor and resources to loss functions was expected from formative research (Langford 2016), the small error is highly suggestive that organizational costs may indeed be the key variable in maintenance planning and scheduling.

Further research into the causal mechanisms for aircraft maintenance is warranted from the preliminary correlative results of this thesis. A full factor-analysis should be investigated, a fault-tree should be developed, and a comprehensive review of the literature on planning and scheduling for maintenance should be undertaken. The rationale for such an intensive and directed investigation, is to examine other aircraft with and without well-order, contiguous data on maintenance. Specifically, there is intense interest in the being able to extrapolate long-term maintenance costs for new aircraft. During the “settling in” early phase of maintenance for sophisticated next-generation aircraft, the maintenance costs may be extremely high and without means to make rational projections of future obligations. The results of this thesis may offer a new approach to projecting long-term maintenance costs for new (and older) aircraft systems.

Apart from the management of MTs, the use of loss function should be considered for other areas of manpower planning and maintenance, particularly when there is competing demand for the same resources by different entities. For such cases, the key stakeholders will have to be identified, where their requirements will form the basis for establishing the value of performance. The corresponding loss functions can then be generated to determine the losses that are projected to have.

APPENDIX (GENERALIZED LOSS FUNCTION)

A key concern for system integration is to develop a set of metrics for determining how well integration is proceeding, [where] leading or lagging indicators are used to gauge the work progress" (Langford 2012, 57). "Metrics are not about trade-offs between what best to do versus what is expedient; [instead] they are used to represent that state of being, the determinant of 'how is it going?' for the integrators and that of the systems engineer(s) and project management" (Langford 2012, 60). "Metrics are focused on the shared value of what the common goal needs to be" (Langford 2012, 60).

In terms of performance measures, there are "objective measures that relate directly to the performance(s) of products and services" (Langford 2012, 128). "Objective measures include any item or combination of items that are categorized as EMMI" (Langford 2012, 128). "Should there be a nominal value, *m*, that is expected as the measure of a function's performance (under various conditions and circumstances), the performance is said to have a target performance value" (Langford 2012, 96). "If there is a variation in performance that is characterized as distributed over a small range of performances centered on the value for the target performance, then the target performance is regulated or controlled by a mechanism" (Langford 2012, 96).

"A function is describable in terms of its performances and its variability in performance quality" (Taguchi 1986). "The functional boundaries of an object are measurable by its performance(s) and its losses that result in achieving those performances" (Langford 2012, 96). "Quality can be associated with the loss, [where it] refers to the consistency of performance, or alternatively, the deviation from a target value, [which is] the performance requirement" (Langford 2102, 98). "Quality [is an indicator] of how well a function is accomplished by the system and is a measure of the loss due to the performance of that function" (Langford 2012, 98). The quality attributed to "a set of objects represents the stability of the performance(s) and the function(s) ascribed to that set of objects [where implications] of poor stability relates to 1) non-delivery of the set of object's functionality, 2) delivery of the set of object's functionality (within the range of performance tolerance), or 3) delivery of performance beyond the

range of specified performance tolerances" (Langford 2012, 98). "For functions, integration is regarded as the relationship between the mechanistic intentions expressed through the design and the performance of objects through their EMMI" (Langford 2012, 98).

A. QUALITY LOSS FUNCTION

Quality can be regarded in different manners; for the purpose of this thesis, it is viewed through an association with a function (Langford 2012, 293). "As a property, quality is then deemed as conformance to performance(s) for that function as objectified through a set of specifications" (Langford 2012, 293). "Functions have performances (a minimum of one per function) where each performance has a quality, [based on] a minimum of one quality measure per each performance" (Langford 2012, 293). Therefore, the "functions of a product or service are completely objectified by performances and qualities" (Langford 2012, 293).

In 1986, "Taguchi proposed a view of quality that relates to cost and therefore a loss measurable in monetary terms" (Taguchi 1986). "This loss accrues not only to the designer, developer, and manufacturer, but also to the customer, user, and society as a whole, where in aggregation these entities represent the seller in a buy–sell relationship" (Langford 2012, 293). This view aids in converting the abstract view of quality to a quantifiable perspective, which provides the way for conduct of cost–benefit analysis. As highlighted, the "approach of developing and applying a quality loss function allows quantitative evaluation of losses caused by variations in behaviors and limits of performance specifications as they associate with various functions of the product" (Choi and Langford 2008).

The "quality loss function developed by Taguchi [in 1990] is used to describe quality in terms of smaller-the-better (STB), larger-the-better (LTB), and nominal-the-best (NTB) characteristics" (Taguchi 1990). "A STB output response results when it is desirable to minimize the performance, with the ideal target for performance being zero, [while the] LTB output response reflects cases when it is desirable to maximize the result, the ideal target being infinity" (Langford 2012, 295). "The NTB characteristic

arises when there is a finite target point (or domain of cooperative agreement) to achieve, often associated through a negotiated outcome, where in this case, upper and lower specification limits exist on both sides of the performance target, representing the maximum or minimum acceptable bounds for the parties of the negotiation" (Langford 2012, 295). This is akin to achieving Pareto efficiency, where "losses for all stakeholders [will have to] be considered and incorporated into a cooperative exchange of benefits and losses, [such that the] agreement between the stakeholders is defined as a position whereby neither stakeholder has an unfair or disproportionate advantage" (Langford 2012, 335). The STB and LTB characteristics are shown in Figure 6, and the NTB characteristic is shown in Figure 7.

Figure 6. "Smaller-the-Better (STB) and Larger-the-Better (LTB) Characteristics" (from Langford 2012, 337)

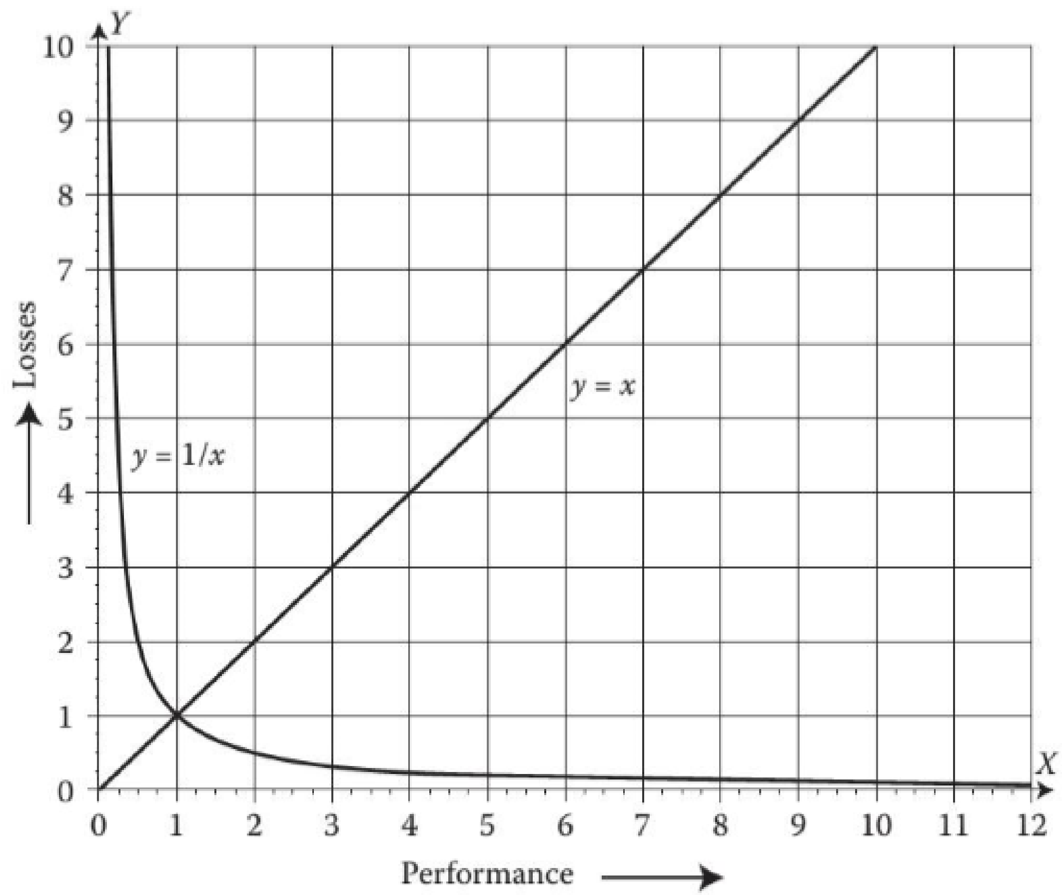
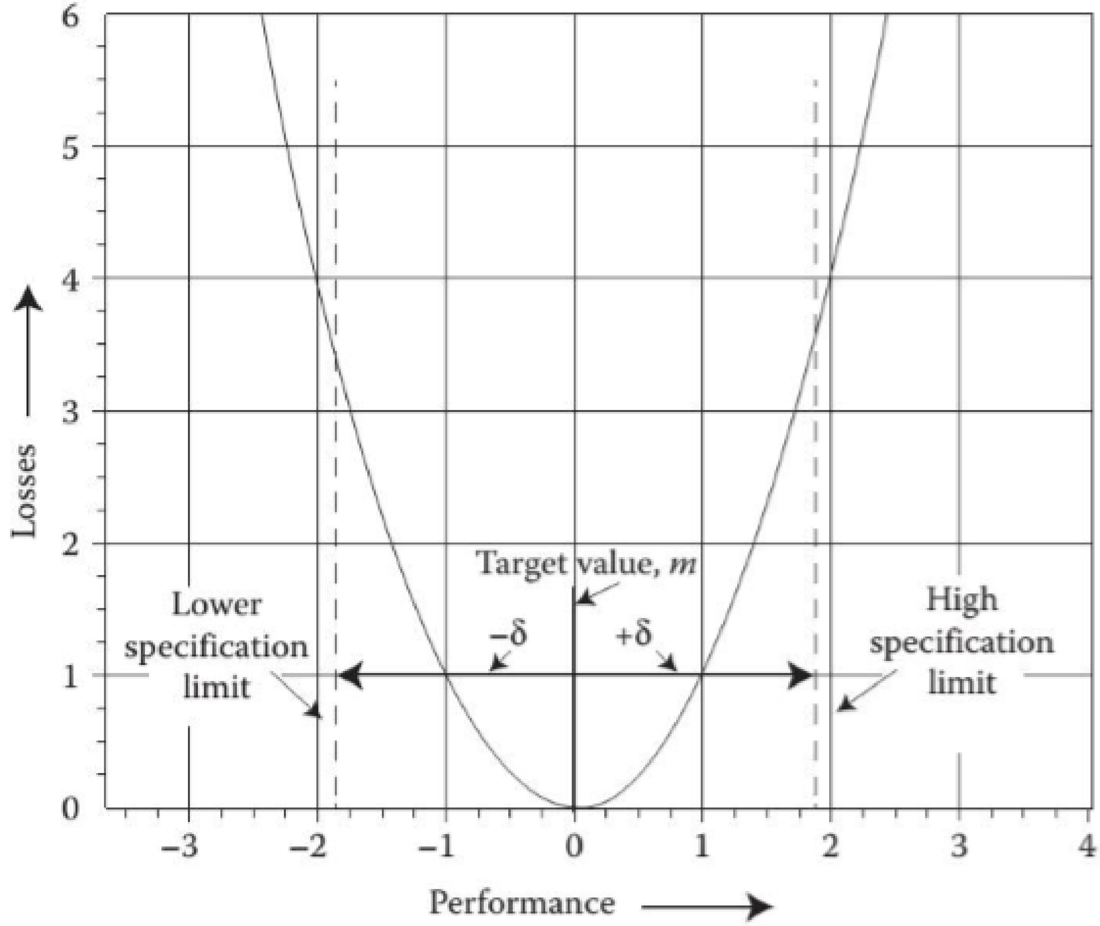
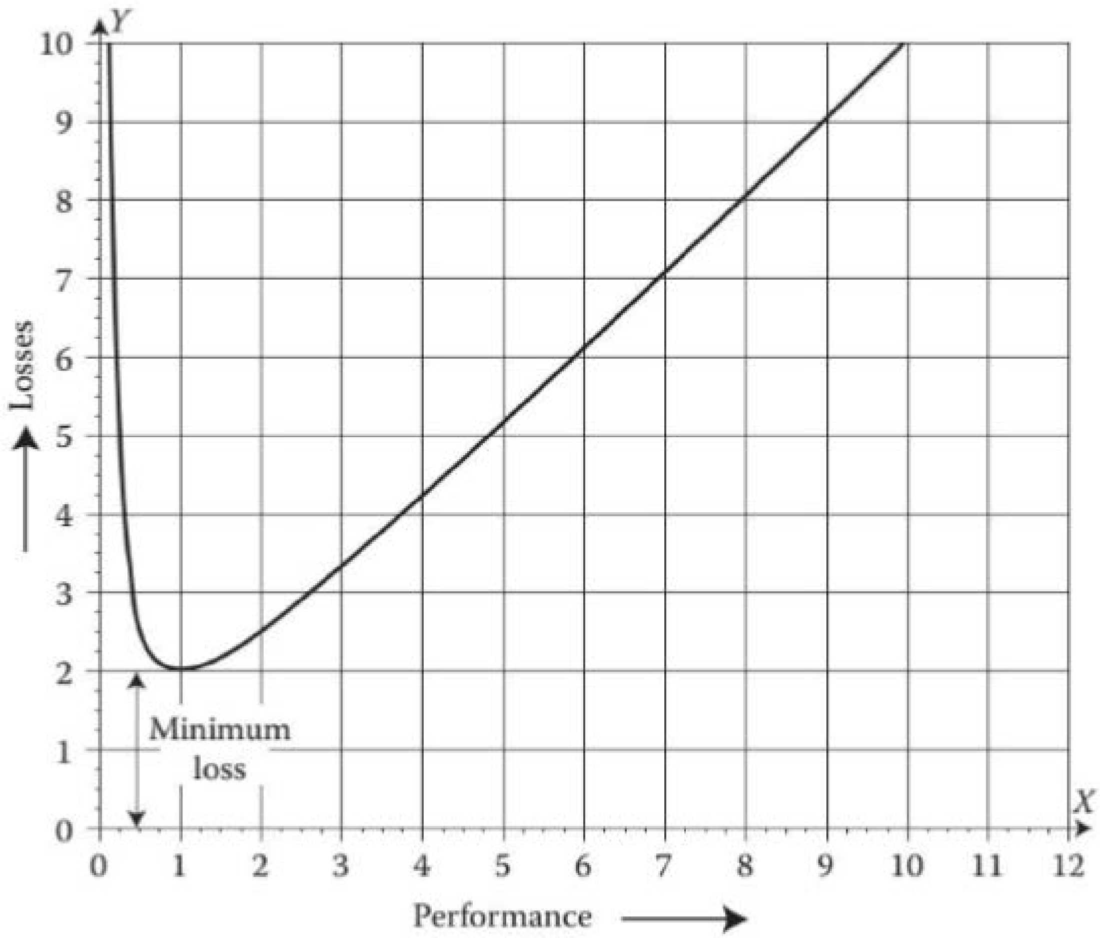


Figure 7. Nominal-the-Best (NTB) Characteristics (from Langford 2012, 336)



For the STB and LTB curves, an addition of both curves results in a representation of negotiation, which is related to a state of minimum loss attained by both parties (Langford 2012, 336). The result is shown in Figure 8.

Figure 8. Combining "Smaller-the-Better (STB) and Larger-the-Better (LTB) Characteristics" (from Langford 2012, 337)



"For each quality characteristic—NTB, STB, and LTB—there exists a function that uniquely defines the relationship between economic loss and the deviation of the quality characteristic from its target value" (Langford 2012, 298).

"Taguchi has [demonstrated] through practice that the quadratic representation of the quality loss function to be an efficient and effective way to assess the loss due to deviation of a quality characteristic from its target value" (Langford 2012, 298).

"For a product with a target value m, from a customer's perspective, $m \pm \Delta o$ represents the deviation at which functional failure of the product's or service's component occurs" (Langford 2012, 298).

“When a product is manufactured or a service is provided with its quality characteristic at the extremes, $m + \Delta 0$ or $m - \Delta 0$, some measure to counter the loss must be undertaken by the customer” (Langford 2012, 298). A loss function with the characteristic of NTB is described as follows:

Nominal-the-best

$$L = k(y - m)^2 k = \frac{A_0}{\Delta_0^2} \tag{9}$$

“where k is a proportionality constant and can be described as the cost of each unit (returned, modified, reworked) divided by the range limits of process variability divided by two; y is the measure of performance (e.g., output) for a given function; m is the target value of y; and A_o is the loss per unit that encompasses the life cycle of the unit that must be expended to mitigate loss, for example countermeasure” (Langford 2012, 299). “The loss function can also be determined for cases when the output response is an STB response, [where based on setting] the target value for performance at zero, the loss function is described as follows” (Langford 2012, 299):

Smaller-the-better

$$L = ky^2 k = \frac{A_0}{y_0^2} \tag{10}$$

“where A_o is the consumer loss and y_o is the consumer tolerance” (Langford 2012, 299). “For an LTB output response where the target is infinity, the loss function can be expressed as follows” (Langford 2012, 299):

Larger-the-better

$$L = k\frac{1}{y^2} k = A_0 y_0^2 \tag{11}$$

B. GENERAL QUALITY LOSS FUNCTION

"A general quality loss function is required to account for changes in the allowable variance from a performance's target value." where in this case, a shape parameter is introduced so as to govern the amount of losses (Langford 2012, 299). "The following seven assumptions are needed to develop a general quality loss function" (Langford 2012, 342):

- "The total quality loss (*Ln(x)*) consists of the stakeholders' loss plus unknown losses.
- If the level of quality equals the target value of the quality (i.e., *m*), the total quality loss is to be zero (or the minimum loss that is inherent in the system).
- If the acquisition phase is production and deployment, the value of shape parameter *n* is equal to two.
- The minimum value of a shape parameter is close to zero and the value of the shape parameter in the concept refinement phase of the acquisition phases varies from zero to one.
- When the acquisition phases are the technology development or system development and demonstration phase, the range value of shape parameter varies from greater than one to less than two.
- After the production and deployment phase, the value of the shape parameter is greater than two.
- The probability distribution of the quality response remains the same regardless of the acquisition phases" (Langford 2012, 342) .

To facilitate derivation of the general loss function, the following notations are used (Langford 2012, 342–343):

"C_b: Baseline cost with a constant value.

C_s: If the type of quality characteristic is smaller-the-better, this means a proportionality constant of stakeholder's loss per response of quality. Additionally, if the type of quality characteristic is larger-the-better, it means a proportionality constant of developer's or manufacturer's loss per response of quality.

C_l: If the type of quality characteristic is larger-the-better, this means a proportionality constant of developer's or manufacturer's loss per response of quality. Additionally, if the type of quality characteristic is smaller-the-better, it means proportionality constant of the stakeholder's loss per response of quality.

n: Shape parameter for representing an acquisition phase of a weapon system ($n > 0$). x: Response of quality.

$L_n(x)$: Total quality loss per piece in the case of shape parameter n and quality response x.

L_n: Expected quality loss per piece in the case of shape parameter n and quality response x" (Langford 2012, 342–343).

Based on the seven assumptions listed and Equations 9, 10, and 11, a "general quality loss function can be established as shown by [Equation 12], which covers all quality characteristics such as nominal-the-best, smaller-the-better, as well as larger-the-better" (Langford 2012, 343).

General Quality Loss Function

$$L_n(x) = C_b + C_s x^n + C_l x^{-n} \tag{12}$$

Upon application of the assumption where the quality level is the same as the quality target value into Equation 12, Equations 13 and 14 are obtained (Langford 2012, 343). "If the response of quality equals to the target value (i.e., m), the total quality loss is

to be zero, [Equation 13], and the result of differentiation for the response of quality having the target value (i.e., *m*) is also equal to zero as per [Equation 14]" (Langford 2012, 343).

$$L_n(m) = C_b + C_s m^n + C_l m^{-n} = 0 \tag{13}$$

$$L_n'(m) = nC_s x^{n-1} - nC_l x^{-n-1} = 0 \tag{14}$$

"If the specific value of *n* is included into [Equations 13 and 14], the general loss function is obtained as follows, where if the value of *n* equals to one, [Equations 15 and 16] are obtained" (Langford 2012, 343):

$$L_1(m) = C_b + C_s m^1 + C_l m^{-1} = 0 \tag{15}$$

$$L_n'(m) = C_s m^0 - C_l m^{-2} = 0 \tag{16}$$

Upon solving Equations 15 and 16, Equation 17 is obtained (Langford 2012, 343).

$$C_l = C_s m^2,\ C_b = -2C_s m \tag{17}$$

If *n* equals to two, Equations 18 and 19 are obtained (Langford 2012, 343):

$$L_2(m) = C_b + C_s m^2 + C_l m^{-2} = 0 \tag{18}$$

$$L_2'(m) = 2C_s m - 2C_l m^{-3} = 0 \tag{19}$$

After solving Equations 18 and 19, Equation 20 is obtained.

$$C_l = C_s m^4,\ C_b = -2C_s m^2 \tag{20}$$

After carrying out iterations in the previously mentioned manner, a quality loss function table is generated as per Table 2.

Table 6. Quality Loss Function Table (from Langford 2012, 344)

n	C_l	C_b	$L_n(x)$
1	$C_l = C_s m^2$	$C_b = -2C_s m^1$	$L_1(x) = -2C_s m^1 + C_s x^1 + C_s m^{2\times 1} x^{-1}$
2	$C_l = C_s m^4$	$C_b = -2C_s m^2$	$L_2(x) = -2C_s m^2 + C_s x^2 + C_s m^{2\times 2} x^{-2}$
3	$C_l = C_s m^6$	$C_b = -2C_s m^3$	$L_3(x) = -2C_s m^3 + C_s x^3 + C_s m^{2\times 3} x^{-3}$
4	$C_l = C_s m^8$	$C_b = -2C_s m^4$	$L_4(x) = -2C_s m^4 + C_s x^4 + C_s m^{2\times 4} x^{-4}$
n	$C_l = C_s m^{2n}$	$C_b = -2C_s m^n$	$L_n(x) = -2C_s m^{2n} + C_s x^n + C_s m^{2n} x^{-n}$

From the last row in Table 2, the general quality loss function is thus detailed as per Equation 21.

$$\begin{aligned} L_n(x) &= -2C_s m^n + C_s x^n + C_s m^{2n} x^{(-n)} \\ &= -2C_s m^n + C_s x^n (1 + m^{2n} x^{(-2n)}) \end{aligned} \tag{21}$$

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